Femtosecond laser pre-pulse technology for LPP EUV source

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FS Laser

Laser	Generator	Tsunami	Spectra Physics
	Regenerative amplifier	Spitfire	Spectra Physics
	Autocorrelator	Pulse Scout	Spectra Physics

Laser parameters

Wavelength	800 nm
Pulse energy	2.3 mJ
Duration(FWHM)	50 fs ÷ 80 ps
Gaussian beam energy profile	
Minimum focal spot size at F=200 mm(FWHM)	50 um
Average power density in focal spot	$3*10^{15}$ W/cm^2
PRR	1 kHz

Droplet

Sn-In eutectic alloy (48%/52% atomic composition)

Operating temperature	140°C
Size ∅	40, 50, 60, 70 um
Velocity	≈ 2-4 m/s
Interaction zone	≈ 1 cm from nozzle.

Why we used In-Sn alloy

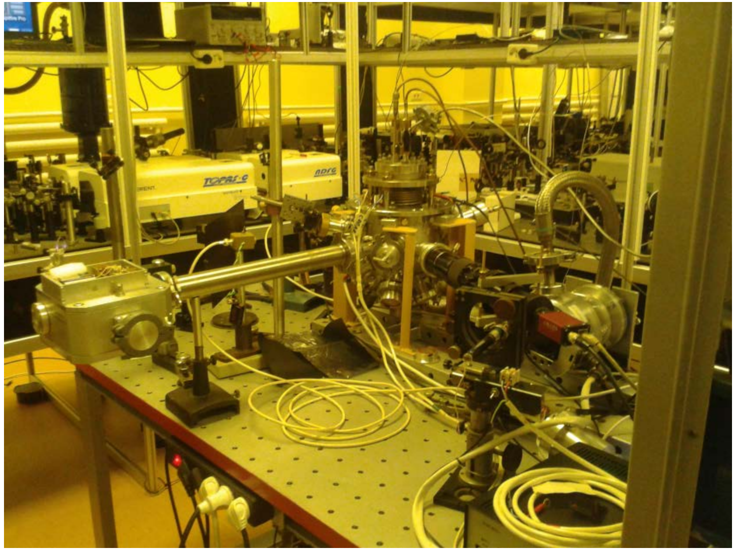
Physical quantity		In	Sn	Δ, %
Atomic number		49	50	2
Atomic weight		114.82	118.71	3.3
Density (near r.t.), $g*cm^3$		7.31	7.36	0.7
Liquid density (at melting point) , $g*cm^3$		7.02	6.99	0.4
Molar heat capacity, $J*mol^{-1}*K^{-1}$		26.74	27.11	1.1
Atomic radius, pm		142	139	2.1
Surface tension, $din*cm^{-1}$		559	554	0.9
Melting point, ^{0}C		156.6	231.9	16
Ionization potentials	I	5.78	7.33	21
	II	18.8	14.6	22
	III	28.0	30.7	8.9
	IV	58	46.5	19.8
	V	77	81	3.7
	VI	98	103	4.9
	VII	120	126	4.8
	VIII	144	150	4
	IX	178	176	1.1
	X	204	213	4.2

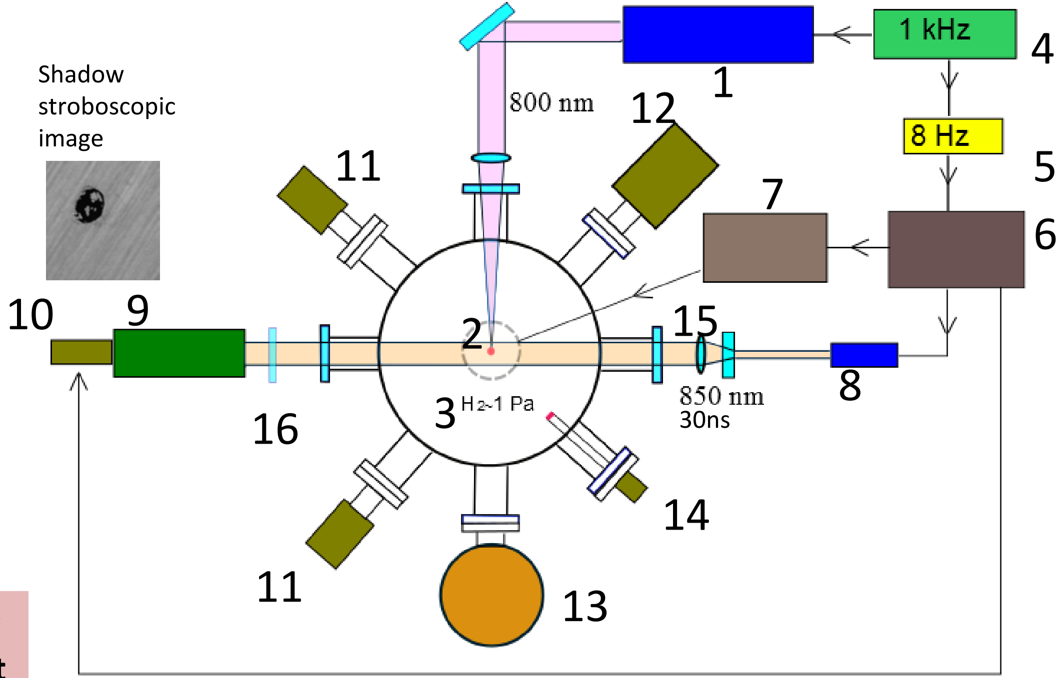
Physical quantity	Sn (300° C)	In–Sn alloy (200° C)
Surface tension,din/cm	538	534
Kinematic viscosity, cSt	0.24	0.25

- Main physical properties of In, Sn and In-Sn alloy are very similar
- Replacement of Sn on In-Sn eutectic alloy allows to use much more reliable experiments because of lower work temperature.
- The alloy may be used as working substance in LPP EUV source. Conversion efficiency of LPP EUV source by using the alloy is about 70% from one by using pure Sn as working substances.

In-Sn eutectic alloy can be used in modeling experiments for Sn droplet in pre-pulse technology of LPP EUV sources.

Synchronization diagram and DG+FS laser setup



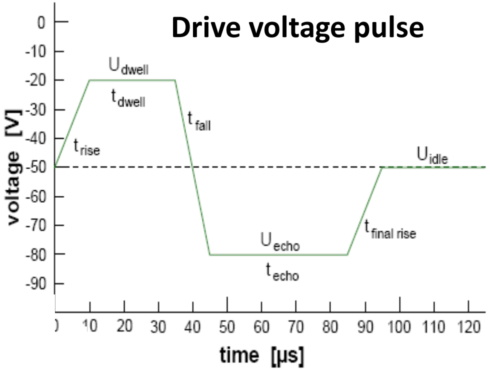


Multistage hit technology of laser beam into droplet

1- FS laser, 2- DG, 3- vacuum chamber, 4- driving generator, 5- frequency divider, 6-delay generator, 7- DG controller, 8- diode laser (IL30C, 850nm, 30ns), 9- long distance microscope (K2 DistaMax), 10-CCD camera (Manta MG-145B), 11- Faraday cup, 12- ion spectrograph, 13- pump, 14- tungsten filament, 15- beam formation optics (diffuser+lens), 16- band pass filter (850nm).

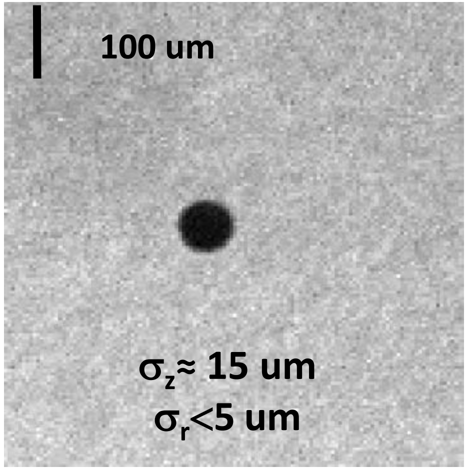
Droplet generator operation

DoD type nozzle based on annular piezoelectric actuator (MJ-SF-002 MicroFab Tech)

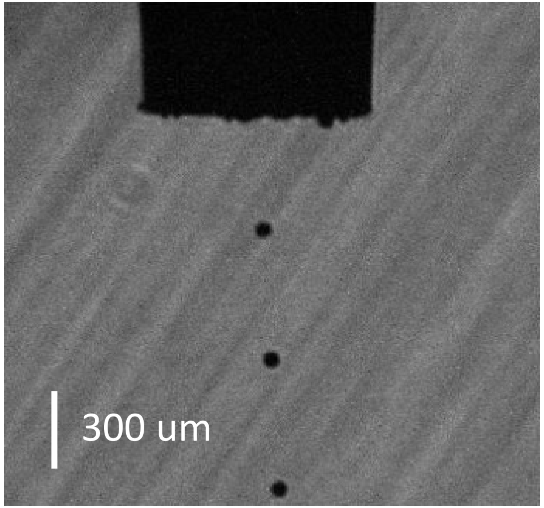


Shadow stroboscopic images 60um droplet

8 Hz, 10mm from nozzle



Pulse train at 5kHz run, v ≈ 2.5 m/s



We have more than 6 controlled parameters of driving pulse !

- **Observed area 4.7 x 3.5 mm,**
- **Spatial resolution 3.7 um**
- **Exposure time (laser pulse duration) 30 ns**

Sets of used experimental parameters

Variable parameters :

- Droplets size
- Laser pulse durations
- Laser pulse energy
- Focal spot sizes

Constant parameter:

PRR of DG 8 Hz

PRR of FS laser 1 kHz

∅40 um, E_{las}=2.3 mJ

1. 50 fs, 50 um
2. 200 fs, 50 um
3. 400 fs, 50 um
4. 800 fs, 50 um
5. 1.5 ps, 50 um

∅ 50 um, E_{las}=2.3 mJ

50 fs, 50 um

400fs, 50 um

∅ 60 um, E_{las}=2.3 mJ

1. 50 fs, 50 and 100 um
2. 100 fs, 50 and 100 um
3. 200 fs, 50 and 100 um
4. 450 fs, 50 and 100 um
5. 800 fs, 50 and 100 um
6. 1.5 ps, 50 and 100 um
7. 3 ps, 50 and 100 um
8. 5.3 ps, 50 and 100 um
9. 80 ps, 50 um

∅ 60 um, E_{las}=1.3 mJ

50 fs, 50 and 100 um

∅ 60 um, E_{las}=0.4 mJ

50 fs, 50 um

∅ 70 um, E_{las}=2.3 mJ

50 fs, 50 um

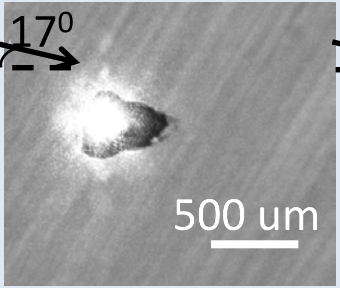
- Delay between FS and diagnostic lasers 0..20 us
- >160 images in each delay

Droplet deformation at τ_{las}= 50 fs

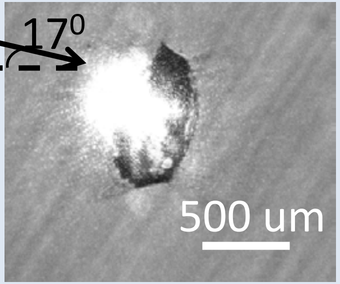
E_{las}=2.3mJ ∅ 60 um

Laser beam direction

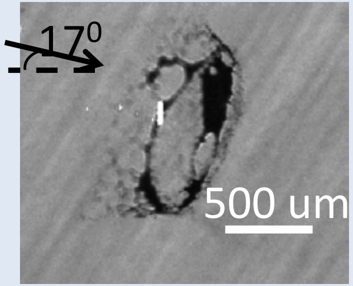
Focal spot 50 um,
I=3*10^{15}W/cm^2



Δ t = 2.0 us



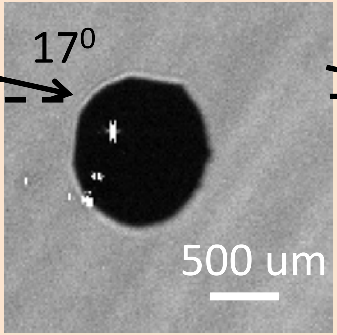
Δ t = 3.0 us



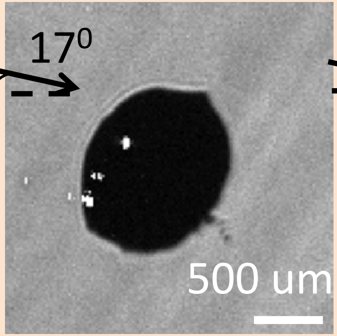
Δ t = 4.0 us

Laser beam direction

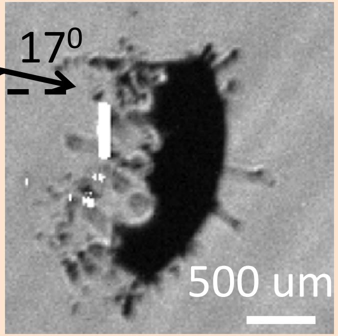
Focal spot 100 um,
I=7.5*10^{14} W/cm^2



Δt = 3.0 us



Δ t = 4.0 us



Δ t = 7.0 us

Δt –delay between FS laser and diagnostic diode laser

The images at different delays belong to different droplets, but deformed images are reproduced very well.

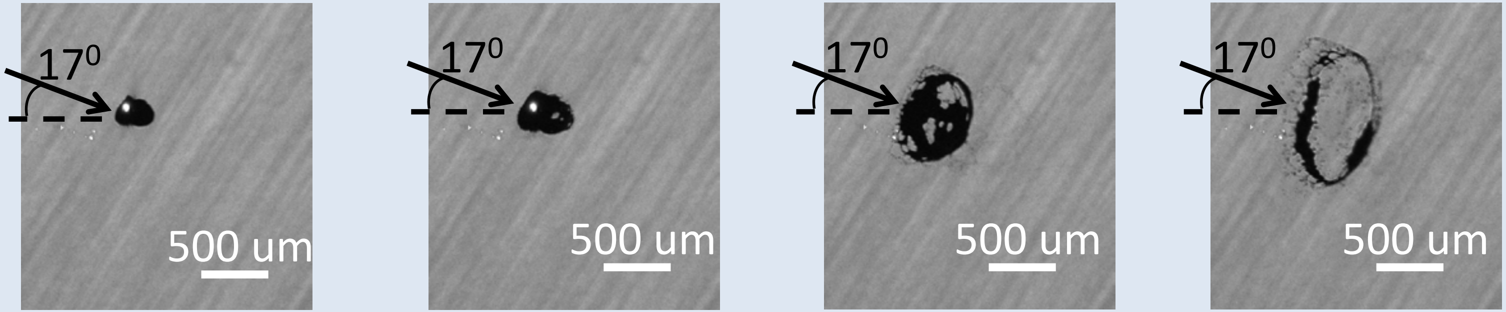
Main difference from ns PP: deformed droplets have shape of hollow thin 3D shells!!

Droplet deformation at τ_{las}= 100 fs

E_{las}=2.3mJ ∅ 60 um

Laser beam direction

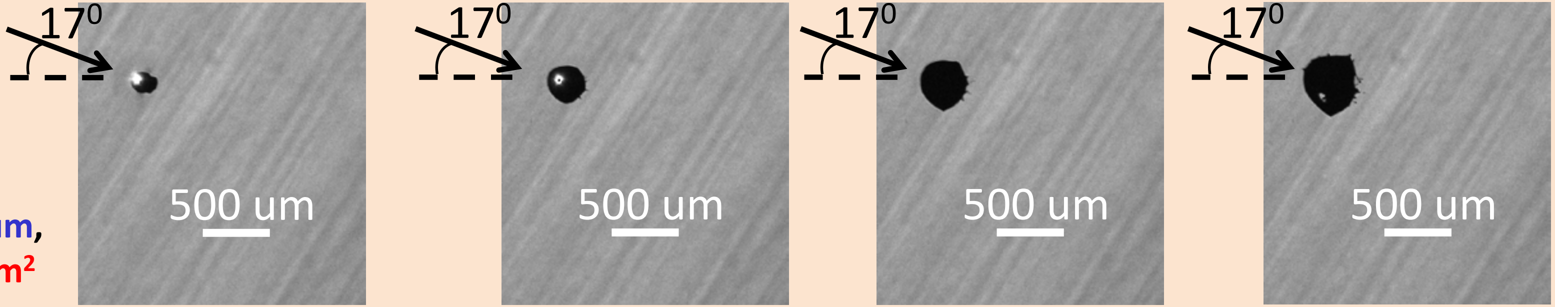
Focal spot 50 um,
I=1.5*10^{15} W/cm^2



Δt = 1.0 us | Δ t = 2.0 us | Δ t = 3.0 us | Δ t = 4.0 us

Laser beam direction

Focal spot 100 um,
I=3.8*10^{14} W/cm^2



Δt = 1.0 us | Δ t = 2.0 us | Δ t = 3.0 us | Δ t = 4.0 us

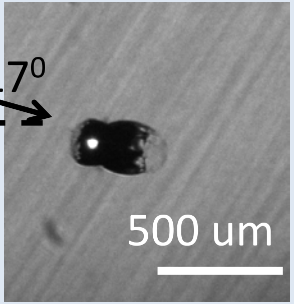
Droplet deformation at τ_{las}= 200 fs

E_{las}=2.3mJ ∅ 60 um

Laser beam direction

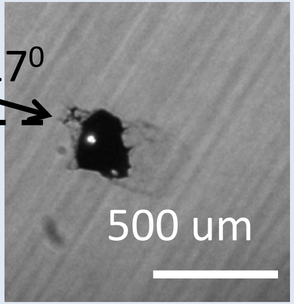
Focal spot 50 um,
$I=7.5*10^{14}$ W/cm^2

17^0



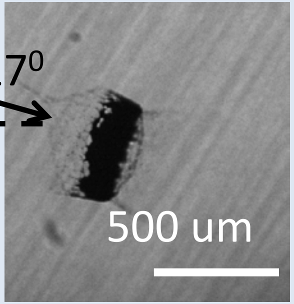
Δt = 1.0 us

17^0



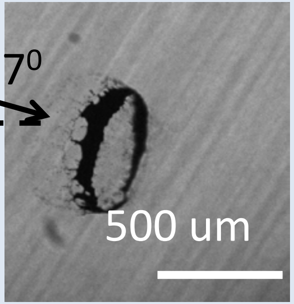
Δt = 2.0 us

17^0



Δt = 3.0 us

17^0

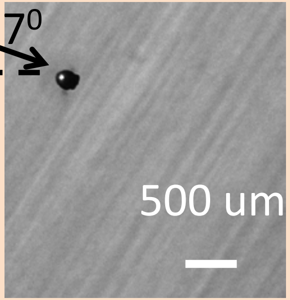


Δt = 4.0 us

Laser beam direction

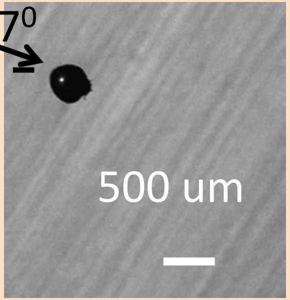
Focal spot 100 um,
$I=1.8*10^{14}$ W/cm^2

17^0



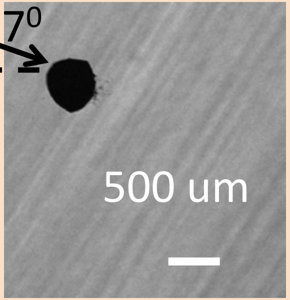
Δt = 1.0 us

17^0



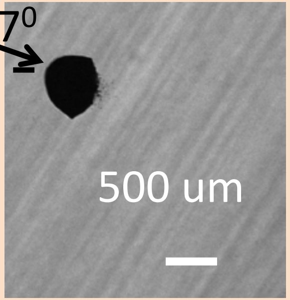
Δt = 2.0 us

17^0



Δt = 3.0 us

17^0



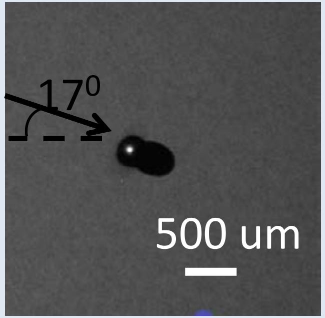
Δt = 4.0 us

Droplet deformation at τ_{las}= 450 fs

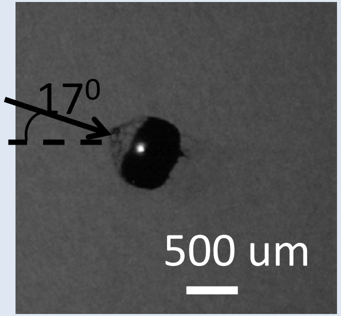
E_{las}=2.3mJ ∅ 60 um

Laser beam direction

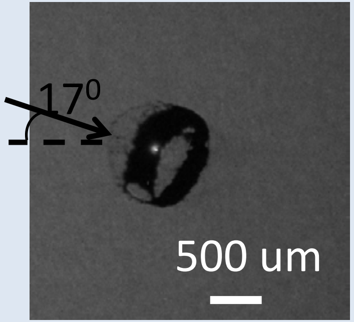
Focal spot 50 um,
I=3.8*10^{14} W/cm^2



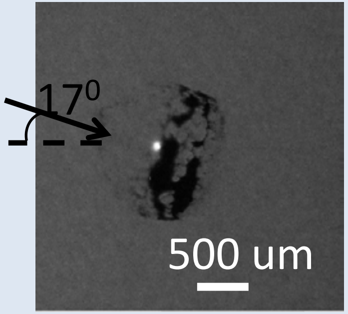
Δt = 1.0 us



Δ t = 2.0 us



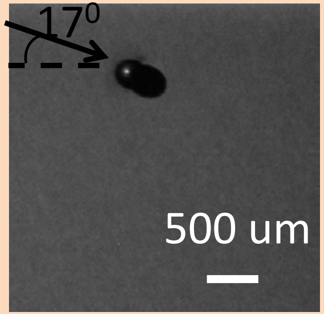
Δ t = 3.0 us



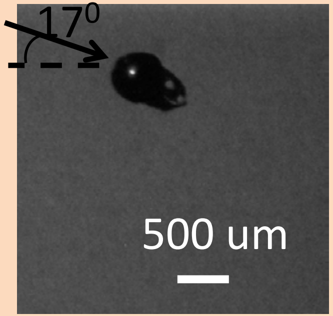
Δ t = 4.0 us

Laser beam direction

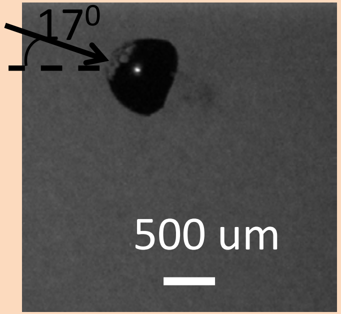
Focal spot 100 um,
I= 10^{14} W/cm^2



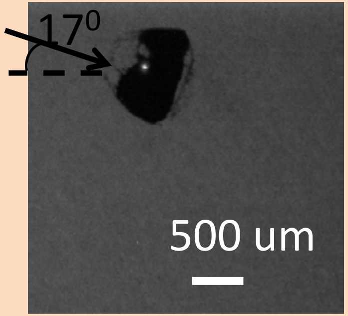
Δt = 1.0 us



Δ t = 2.0 us



Δ t = 3.0 us



Δ t = 4.0 us

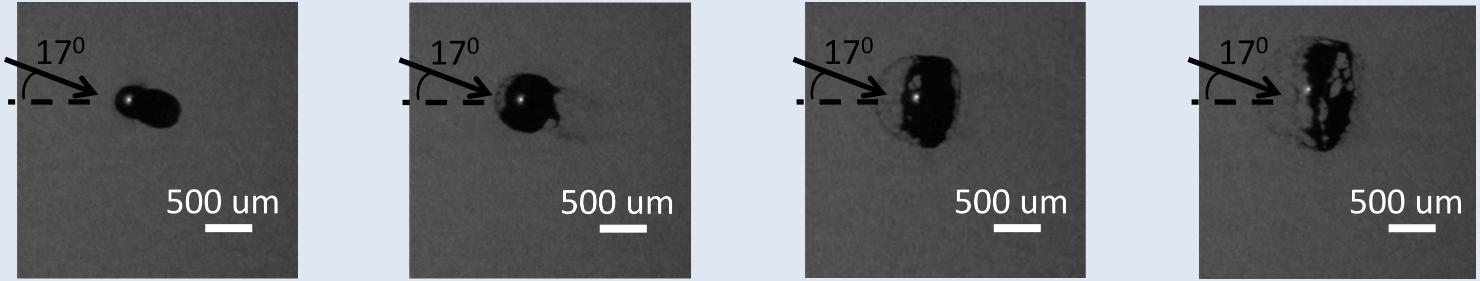
Droplet deformation at τ_{las}= 800 fs

E_{las}=2.3mJ ∅ 60 um

Laser beam direction

Focal spot 50 um,

I=1.8*10^14 W/cm^2

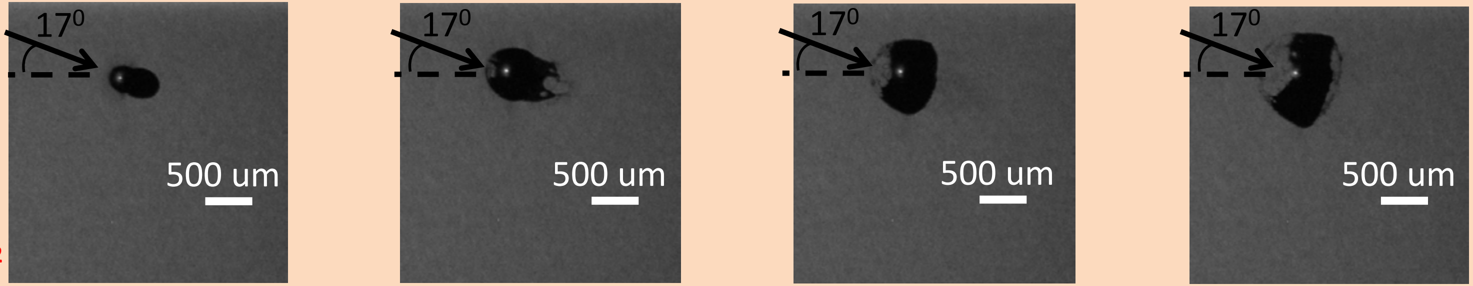


Δt = 1.0 us   Δ t = 2.0 us   Δ t = 3.0 us   Δ t = 4.0 us

Laser beam direction

Focal spot 100 um,

I= 0.45*10^14 W/cm^2

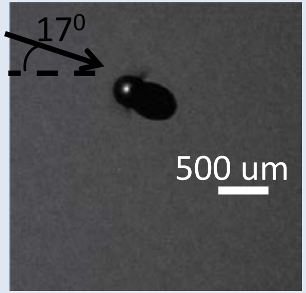


Δt = 1.0 us   Δ t = 2.0 us   Δ t = 3.0 us   Δ t = 4.0 us

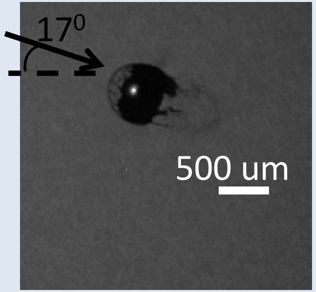
Droplet deformation at τ_{las}= 1.5 ps

E_{las}=2.3mJ ∅ 60 um

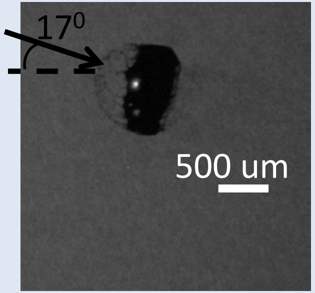
Laser beam direction



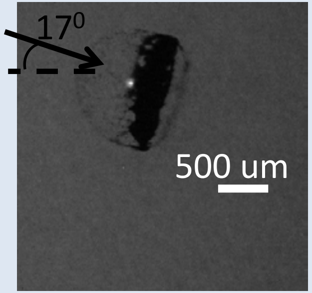
Δt = 1.0 us



Δ t = 2.0 us



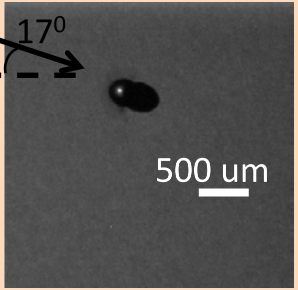
Δ t = 3.0 us



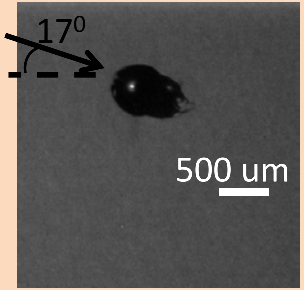
Δ t = 4.0 us

Focal spot 50 um,
I=10^{14} W/cm^2

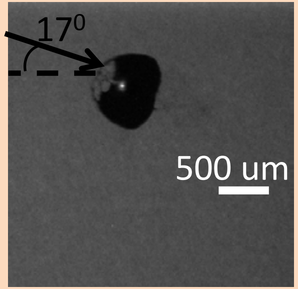
Laser beam direction



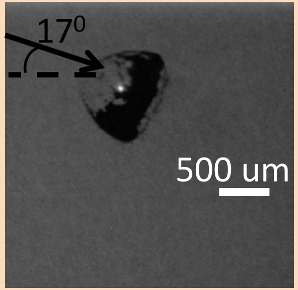
Δt = 1.0 us



Δ t = 2.0 us



Δ t = 3.0 us



Δ t = 4.0 us

Focal spot 100 um,
I= 2.7*10^{13} W/cm^2

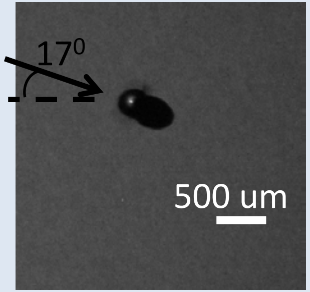
Droplet deformation at τ_{las}= 3 ps

E_{las}=2.3mJ ∅ 60 um

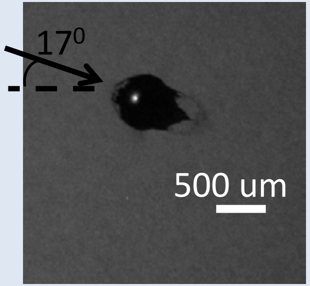
Laser beam direction

Focal spot 50 um,

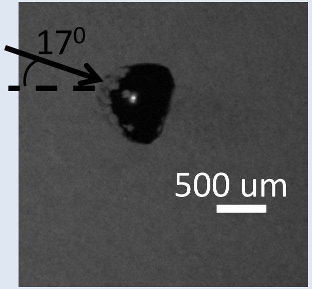
$I=5*10^{13}$ W/cm^2



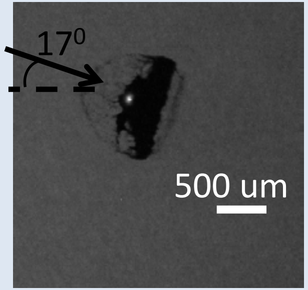
Δt = 1.0 us



Δ t = 2.0 us



Δ t = 3.0 us

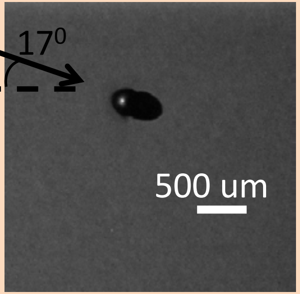


Δ t = 4.0 us

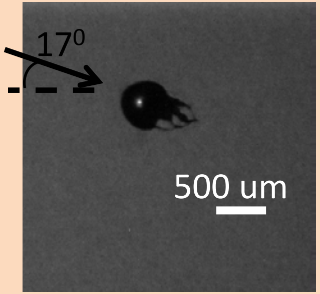
Laser beam direction

Focal spot 100 um,

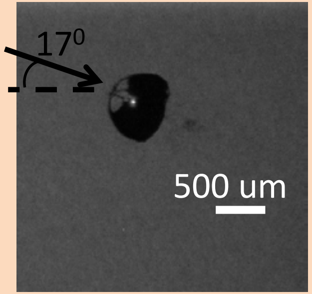
$I= 1.3*10^{13}$ W/cm^2



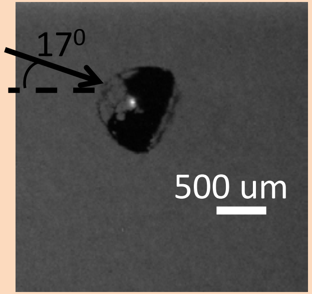
Δt = 1.0 us



Δ t = 2.0 us



Δ t = 3.0 us



Δ t = 4.0 us

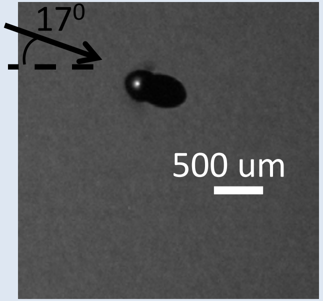
Droplet deformation at τ_{las}= 5.3 ps

E_{las}=2.3mJ ∅ 60 um

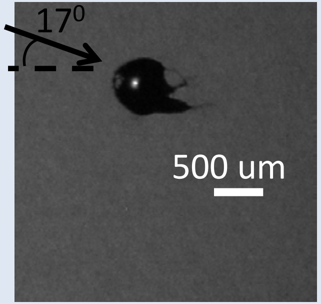
Laser beam direction

Focal spot 50 um,

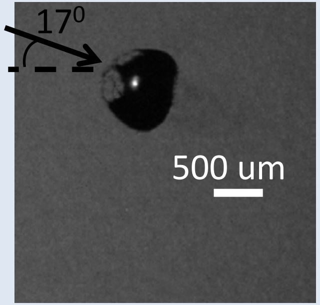
I=2.8*10^{13} W/cm^2



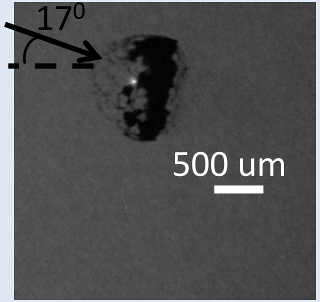
Δt = 1.0 us



Δ t = 2.0 us



Δ t = 3.0 us

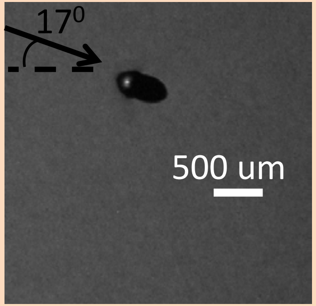


Δ t = 4.0 us

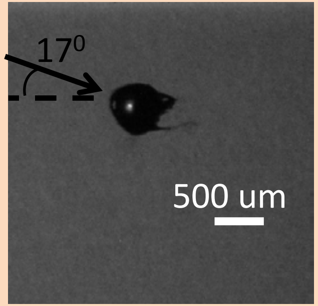
Laser beam direction

Focal spot 100 um,

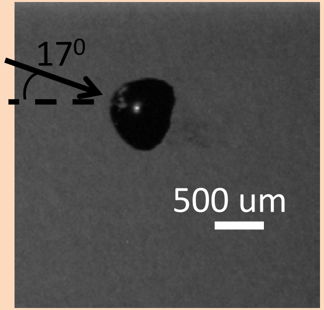
I= 7.4*10^{12} W/cm^2



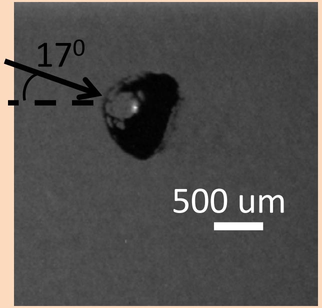
Δt = 1.0 us



Δ t = 2.0 us



Δ t = 3.0 us



Δ t = 4.0 us

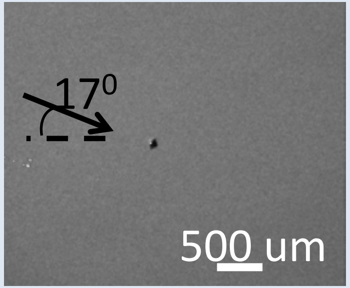
Droplet deformation at $\tau_{las} \approx 80$ ps

E_{las}=2.3mJ $\varnothing$ 60 um

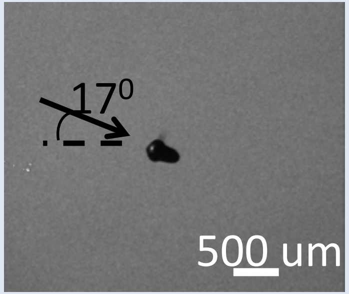
Laser beam direction

Focal spot 50 um,

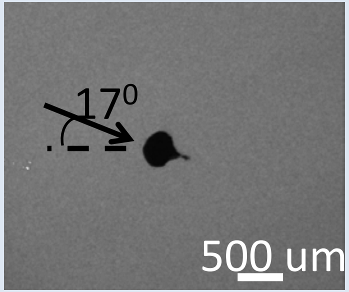
$I = 1.9*10^{12} W/cm^2$



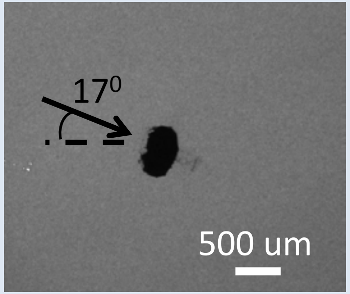
Δt = 1.0 us



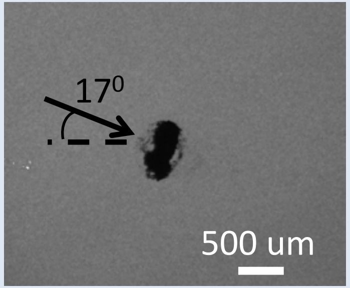
Δ t = 2.0 us



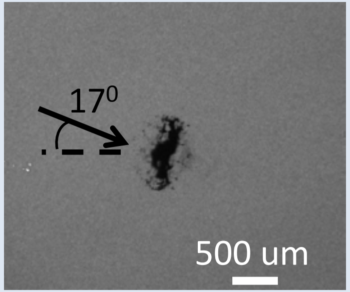
Δ t = 3.0 us



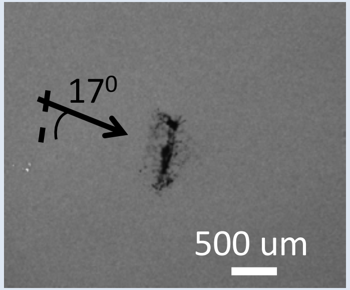
Δ t = 4.0 us



Δt = 5.0 us



Δ t = 6.0 us

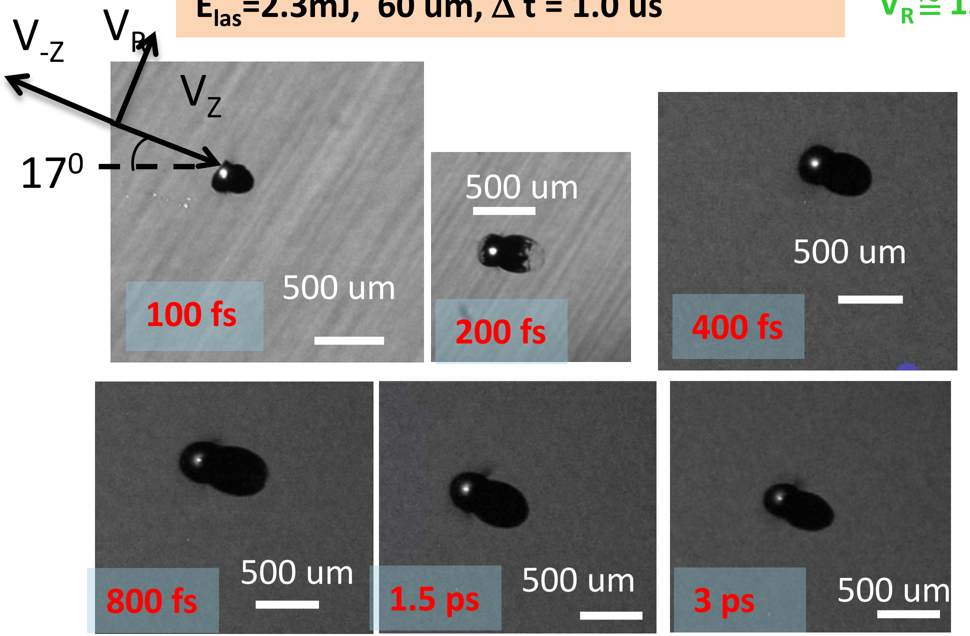


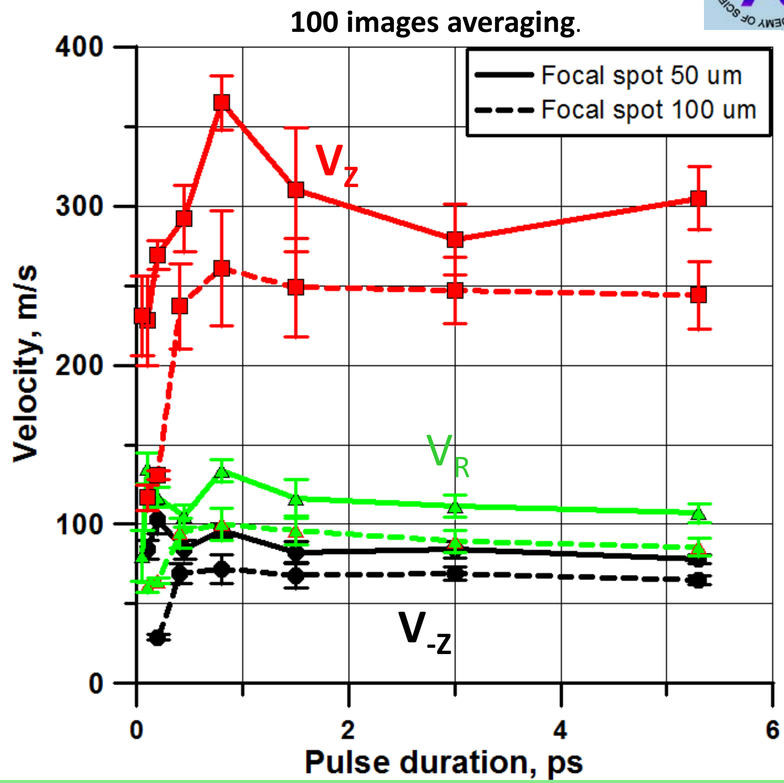
Δ t = 7.0 us

Shell expansion velocity vs pulse duration

Shadowgrams at different laser duration
E_{las}=2.3mJ, 60 um, Δ t = 1.0 us

$V_Z \cong$ 300 m/s
$V_{-Z} \cong$ 80 m/s
$V_R \cong$ 120 m/s





There is weak dependence of droplet expansion velocity on pulse duration at more than 1 ps. Dependence velocity on laser power density for ns lasers $V_Z \approx I^{2/3}$ is not working in this case !

Variety of deformed shapes (some examples)

$\varnothing$ **60 um**

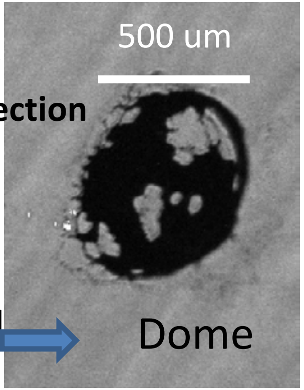
Changing experimental parameters (size of droplet and focal spot, laser pulse duration, laser energy, delay) we can choose the optimal target shape for LPP EUV source from point of view max CE, min debris and high energy ions.

All shapes have been stable from pulse to pulse

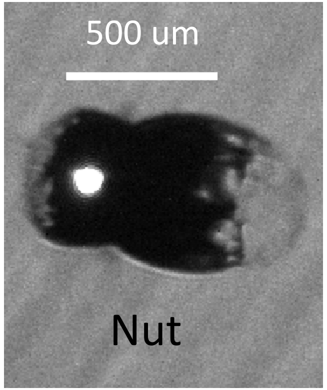
17^0

Laser direction

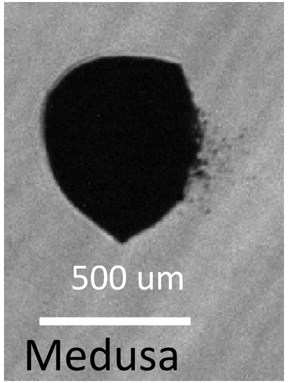
conditional types



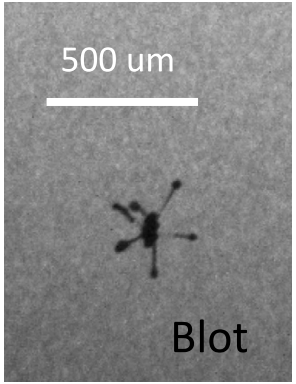
E_{las}=2.3 mJ
SpotSize=50 um
τ_{las}=100 fs
$\Delta\tau$=3 us



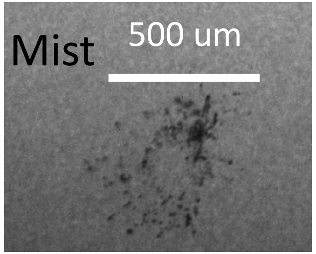
E_{las}=2.3 mJ
SS=50 um
τ_{las}=200 fs
$\Delta\tau$=1us



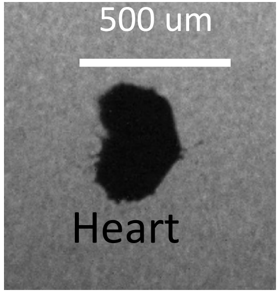
E_{las}=2.3 mJ
SS=100 um
τ_{las}=200 fs
$\Delta\tau$=4 us



E_{las}=1.3 mJ
SS=100 um
τ_{las}=50 fs
$\Delta\tau$=10 us



E_{las}=0.4 mJ
SS=50 um
τ_{las}=50 fs
$\Delta\tau$=10us

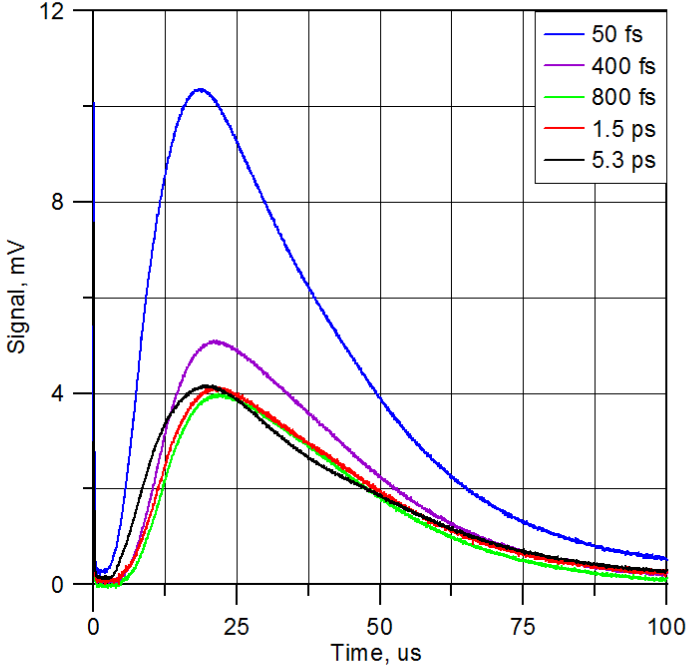


E_{las}=0.4 mJ
SS=50 um
τ_{las}=50 fs
$\Delta\tau$=4 us

Ion flux measurements

Total ion flux

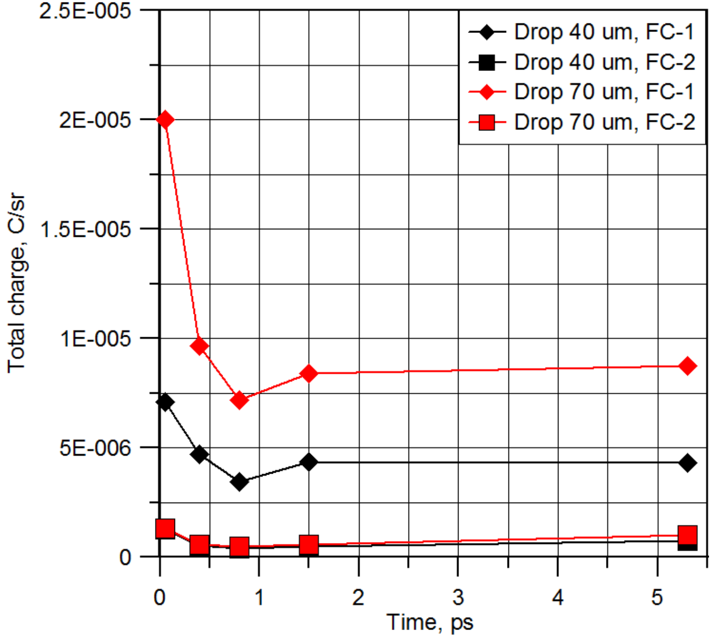
Oscilligrams of total ion current



Droplet ∅ 70 um
∅ 40 um
Focal spot 50 um
FC-1 with amplifier (against laser beam)
FC-2 without amplifier (along laser beam)

Taking into account
FC-1 amplifier gain
FC-1,2 solid angles

Total ion charge vs pulse duration

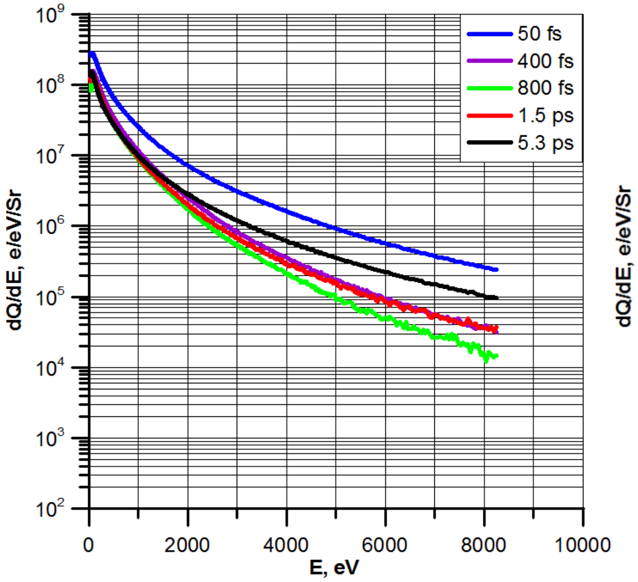


- Total charge of ions flying against laser beam for 70 um droplets is much more than one for 40 um droplet.
- Total charge of ions flying against laser beam is much more than ones flying in along laser beam.
- There is min total charge at 800 fs pulse duration which correlates with max of shell expansion velocities.

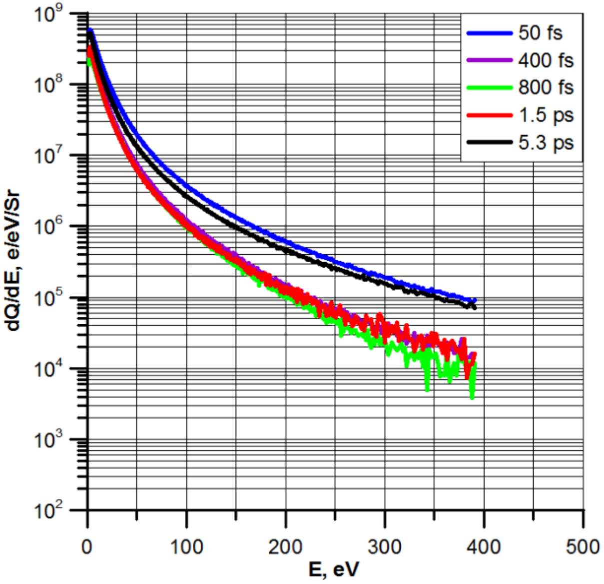
Distribution of total ion charge on ion energy

Droplet ∅ 70 um

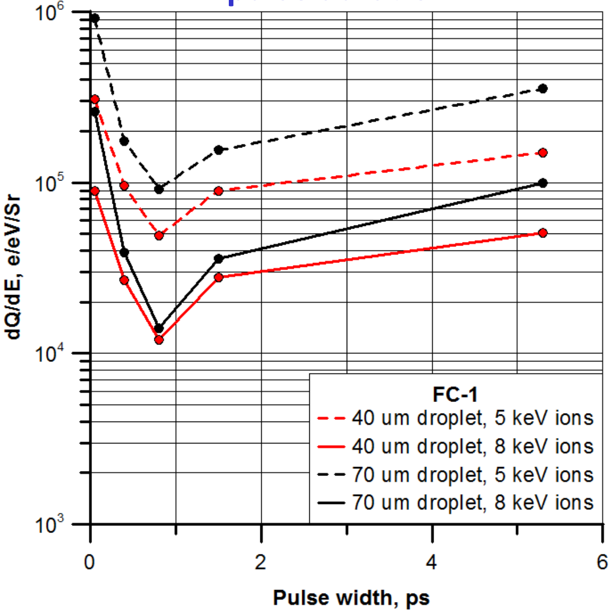
FC-1 against laser beam



FC-2 along laser beam



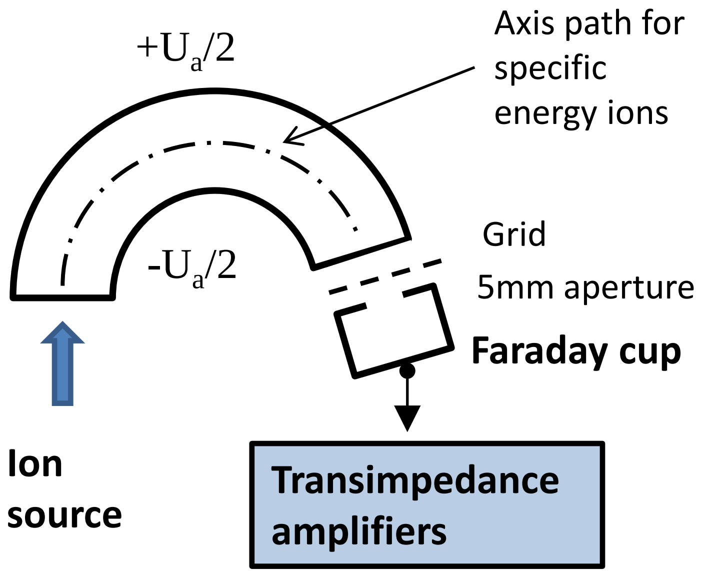
High energy ions charge vs pulse duration



- **High-energy ions fly only in the opposite direction to the propagation of the laser beam.**
- **Maximum number of the high-energy ions observed at 50 fs pulse.**
- **There is minimum of the high-energy ions at 800 fs pulse.**

Ion spectrum measurements

Electrostatic ion energy analyzer based on a cylindrical capacitor



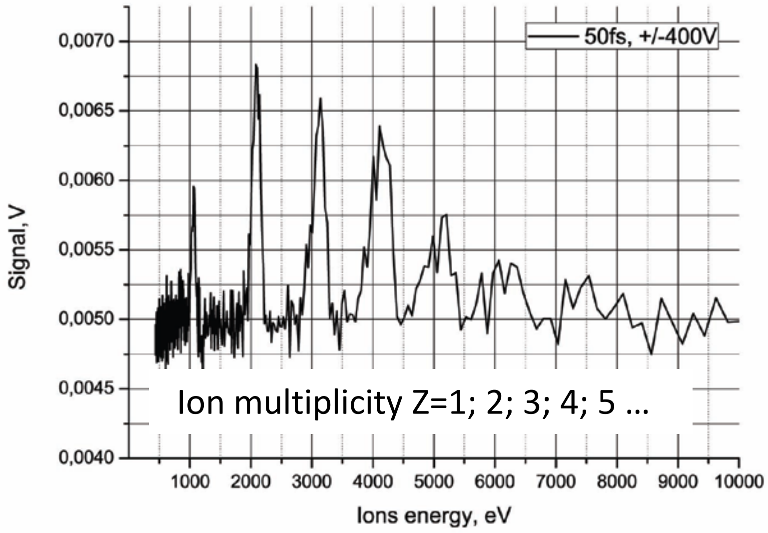
E_{ion} = 1.25*Z*U, U – deflection voltage,
1.25 - energy scaling factor

- Detector — Faraday cup
- Input aperture — 1 mm
- Azimuth angle between laser beam and IS — 30 °
- Angle in vertical plane to the laser beam — 17 °
- Distance to the droplet — 500 mm

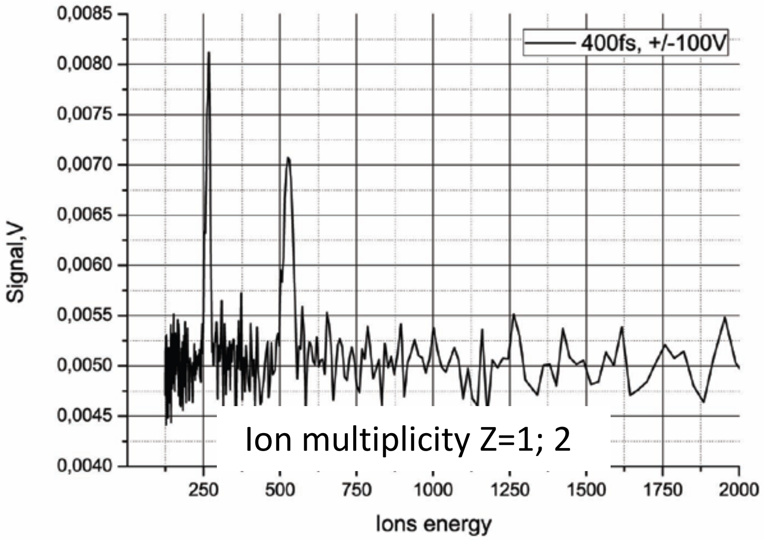
Oscillograms of ion beam current

Droplet ∅ 50 um, focal spot size 50 um

64 measurements averaging.



32 measurements averaging.



τ_{laser} = 50 fs, P=1.5*10^{15} W/cm^2 U = 800 V

τ_{laser} = 400 fs, P=3.8*10^{14} W/cm^2 U = 200 V

Ion multiplicity for 50 fs pulse much more than for 400 fs pulse

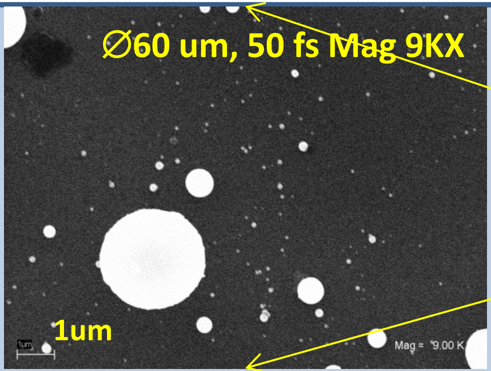
Debris deposition

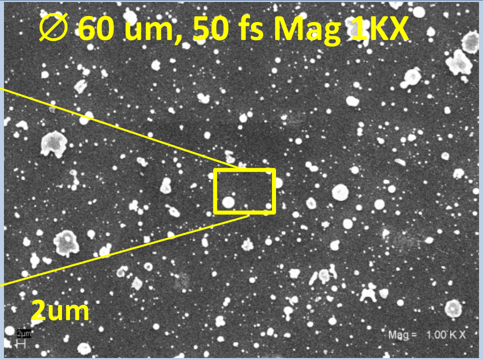
Number of pulses ≈ 25 000

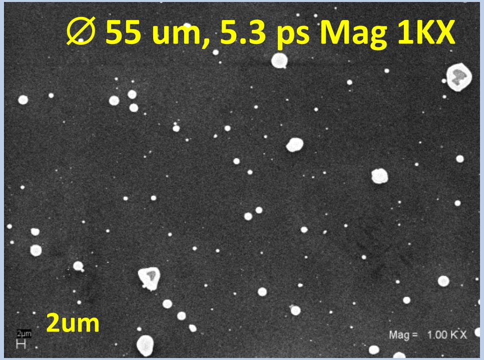
Minimal size of observed debris ≈ 90 nm

Electron microscope photos

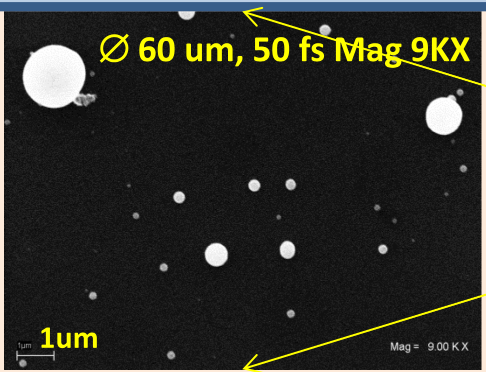
Sample A (along laser beam direction)

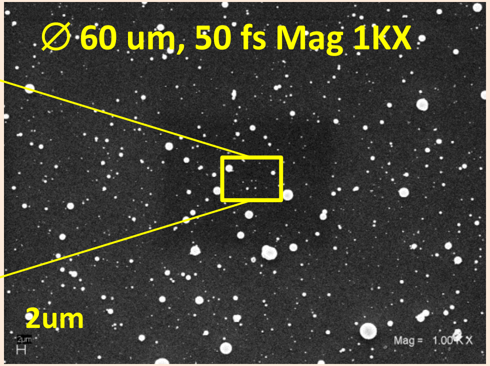


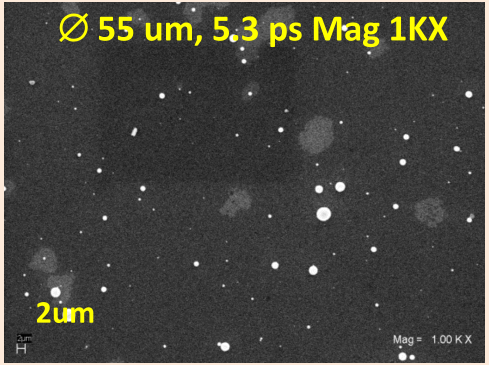




Sample B (against laser beam direction) 60 um, 50 fs

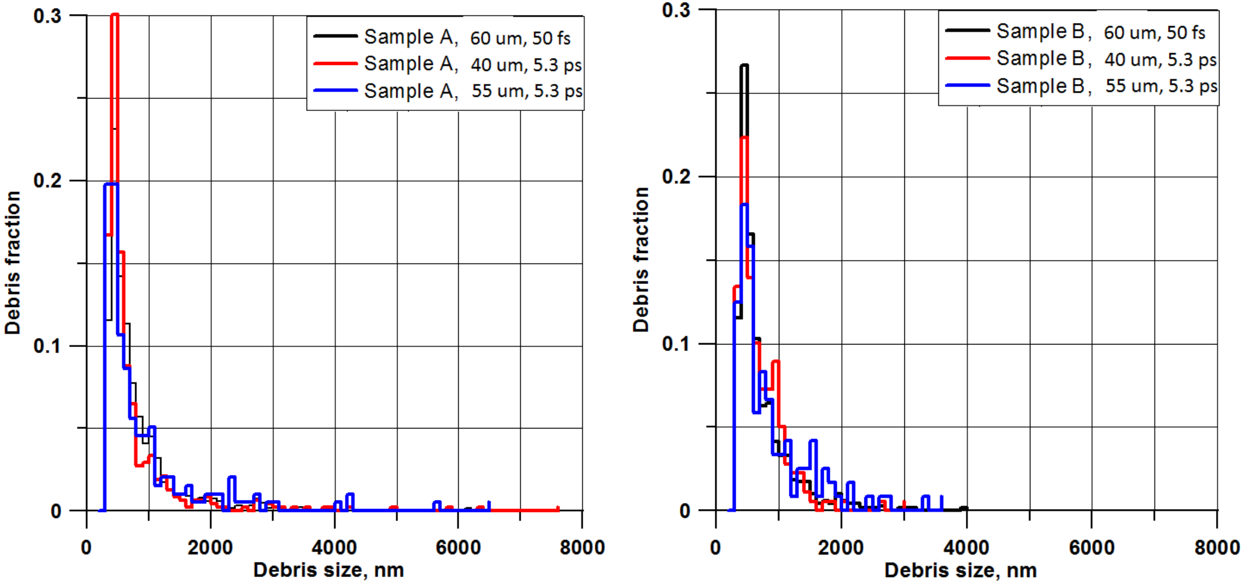






Debris distribution

For particles >250nm, step of particle sizes 100nm



1.Distribution for all modes and both directions are close.
2. Mass of particles flying along laser beam direction are much more than ones flying against laser beam direction

At isotropic scattering of debris masses would be:
For 60um $6.6*10^{-8}$ g/sr
For 55 um $5*10^{-8}$ g/sr
For 40 um $1.9*10^{-8}$ g/sr

Number and mass of debris from single droplet in 1 sr

	60 um, 50 fs	40 um, 5.3 ps	55 um, 5.3 p s
Sample A	≈ 16 300 ($4.9*10^{-8}$ g/sr)	≈ 6 400 ($2.6*10^{-8}$ g/sr)	≈ 2 600 ($1.5*10^{-8}$ g/sr)
Sample B	≈ 9 400 (10^{-8} g/sr)	≈ 2 400 ($0.2*10^{-8}$ g/sr)	≈ 1 600 ($0.37*10^{-8}$ g/sr)

Where is difference?
Vapor?

Summary

- In-Sn droplet deformation and fragmentation dynamic at the action of femto- and picosecond laser in wide band pulse duration from 50 fs up to 80 ps at power density up to $P=3*10^{15}$ W/cm^2 were studied by ultrafast shadowgraph method. Changing experimental parameters it is possible choose the optimal shape of target for LPP EUV source.
- Total ion charge and ion spectrum measurements at action of laser with femto- and picosecond pulse duration on In-Sn droplets were carried out. It is established that high-energy ions up to 8 keV are present only in the opposite direction to the laser beam.
- Debris distributions at interaction of femto- and picosecond laser with In-Sn droplets. It is established that particles flying along laser beam are much more than ones flying against laser beam.

Acknowledgements

We thank ASML company for technical support our experiments.

Thank You for Your Attention